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TRANSMISSION FACTOR EFFECTS ON THE AVERAGE FORWARD RANGE OF COM--ETC(U)
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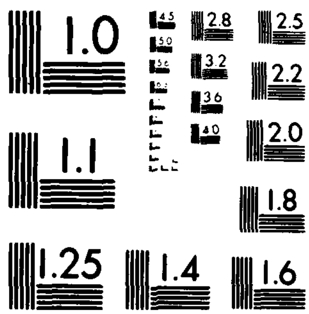

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: HDL-TM-80-10	2. GOVT ACCESSION NO.: AD-A086 590	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): Transmission Factor Effects on the Average Forward Range of Compton Electrons.		5. TYPE OF REPORT & PERIOD COVERED: Technical Memorandum
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): William T. Wyatt, Jr		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Harry Diamond Laboratories, 2800 Powder Mill Road, Adelphi, MD 20783		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Program Ele: 6.21.20.A
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Materiel Development & Readiness Command, Alexandria, VA 22333		12. REPORT DATE: Jan [redacted] 80
		13. NUMBER OF PAGES: 12
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report): UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

DRCMS Code: 612120.H.250011
HDL Project: X759E6

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Compton electrons
EMP

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Compton electrons generated in air by gamma rays produced by nuclear explosions are known to cause transient electromagnetic fields called the electromagnetic pulse (EMP) or radioflash. The average forward range of the Compton electrons in air is a principal factor governing the strength of the EMP. Previous estimates of the average forward range of Compton electrons were based on an energy-independent electron transmission factor. This

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20. Abstract (Cont'd)

investigation uses an energy-independent electron transmission factor to obtain more accurate results. Results from the two methods are in agreement for an incident gamma energy of 1.5 MeV, and disagree by 7 and 10 percent for incident gamma energies of 0.3 and 10.0 MeV, respectively. Simple numerical fits to the new results are included.

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1. INTRODUCTION

Compton electrons generated in the air by gamma rays produced by nuclear explosions are known to cause transient electromagnetic fields called the electromagnetic pulse (EMP) or radioflash. The average forward range of the Compton electrons in the air is a principal factor governing the strength of the EMP caused by bursts in the lower atmosphere within about 10 km of the earth's surface. For bursts at high altitudes, a different treatment of the trajectory of the Compton electrons is necessary.

For low-altitude bursts, previous estimates[1] of the average forward range of Compton electrons produced by collimated monochromatic gamma rays were based on the use of an energy-independent electron transmission factor for the Compton electrons. The transmission factor represents the cumulative effect of small- and large-angle scattering of the electrons, causing the electrons to straggle. Use of an energy-independent transmission factor neglects both the true average Compton recoil energy and the recoil energy dependence upon the scattering angle.

In this investigation, the average forward range is computed using an energy-dependent transmission factor in connection with the Compton angular scattering distribution. This is done for a range of gamma ray energies from 0.3 to 10 MeV. Simple numerical fits to the results are included.

2. METHOD OF CALCULATION

The well-known Klein-Nishina differential scattering cross section for Compton scattering is

$$d(\sigma_e) = 2\pi \sin\theta \, d\theta \, r_o^2 \left[\frac{1}{1+\alpha(1-\cos\theta)}\right]^2 \cdot \left(\frac{1+\cos^2\theta}{2}\right)\left(1+\frac{\alpha^2(1-\cos\theta)^2}{(1+\cos^2\theta)[1+\alpha(1-\cos\theta)]}\right)$$

per electron,

where

θ = gamma scattering angle,

α = gamma energy in units of 0.511 MeV, and

r_o = classical electron radius.

The electron recoil angle ϕ is given by

$$\cot\phi = (1+\alpha)\tan(\theta/2) \ .$$

The scattered gamma energy E' is

$$E\gamma' = E\gamma / [1+\alpha(1-\cos\theta)] \ ,$$

where $E\gamma = 0.511\alpha$ is the incident gamma energy (in MeV). The electron recoil energy E is

$$E = E\gamma - E\gamma' \ .$$

The range of the Compton electron is commonly given in two alternative forms: (1) the practical or extrapolated range or (2) the maximum or CSDA range (i.e., continuous slowing down approximation). The former is obtained from experiments and the latter from slowing-down theory. The extrapolated range is commonly estimated to be about 0.8 of the maximum range. The difference is attributed to multiple scattering of the electrons. Results were obtained in this investigation for an example of each form for electrons in air of density ρ:

(1) $\rho R_{ex} = 0.368E^A, \ A = 1.26-0.064 \ \ln E$ (cm),

(2) $\rho R_o = 0.61E^2/(E+0.26)$ (cm),

where the first formula is a frequently used approximation and where the latter formula is due to Longmire as cited by Malik.[1] As suggested,

$$R_{ex} \approx 0.8 \ R_o \ .$$

The electron transmission factor (also called "transmitted number fraction") has been measured by Ebert et al,[2] who suggested the following expression for the transmission factor T(x):

[1] John S. Malik, The Compton Current, Los Alamos Scientific Laboratory, Defense Atomic Support Agency, 1882-1 (5 November 1965).

[2] P. J. Ebert, A. F. Lauzon, and E. M. Lent, Lawrence Radiation Laboratory, UCRL-71462 (December 1968), as cited by J. A. Lonergan and D. C. Shreve, Parametric Fit to Electron Transport Properties, Proceedings of the National Symposium on Natural and Manmade Radiation in Space, E. A. Warman, ed., National Aeronautics and Space Administration, TM X-2440 (January 1972).

$$T(x) = \exp\{-A(x/R_{ex})^B\} \ ,$$

where

$$A = (1-1/B)^{1-B} \ ,$$

$$B = \left[\frac{387\ E}{Z(1+7.5\times10^{-5}\ ZE^2)}\right]^{1/4} \ , \text{and}$$

Z = the atomic number (7.2 for air).

The following integrals define Compton total cross section (σ_e), average Compton recoil energy (E), average forward direction cosine of the Compton electron ($\overline{\cos\phi}$), and Compton electron average forward range ($\overline{R}$):

$$\sigma_e = \int_{\theta=0}^{\theta=\pi} d(\sigma_e) \ ,$$

$$\overline{E} = \frac{1}{\sigma_e}\int_{\theta=0}^{\theta=\pi} E\ d(\sigma_e) \ ,$$

$$\overline{\cos\phi} = \frac{1}{\sigma_e}\int_{\theta=0}^{\theta=\pi} \cos\phi\ d(\sigma_e) \ ,$$

$$\overline{R} = \frac{1}{\sigma_e}\int_{\theta=0}^{\theta=\pi} \hat{R}(E)\cos\phi\ d(\sigma_e) \ .$$

The average electron range $\hat{R}$ is

$$\hat{R}(E) = -R_{ex}\int_{x=0}^{\infty} x\,\frac{dT(x)}{dx}\,dx \ ,$$

which, using the Ebert form for T(x), is easily found to be

$$\hat{R}(E) = R_{ex}a^{a}\Gamma(2-a) \ ,$$

where

$$a = 1-1/B \ .$$

The ratio $\hat{R}/R_{ex}$ is tabulated for a few values of electron energy E in table 1. Energy-independent values of 2/3 and 0.63 have been used previously as cited by Malik.[1]

TABLE 1. AVERAGE ELECTRON RANGE $\hat{R}$ AS A FRACTION OF EXTRAPOLATED RANGE R_{ex}, USING EBERT'S FORMULA

Electron energy E (MeV)	Ratio $\hat{R}/R_{ex}$
0.03	0.7488
0.1	0.6243
0.5	0.6404
1.0	0.6650
1.5	0.6812
2.0	0.6932
2.5	0.7027
3.0	0.7104
3.5	0.7170
5.0	0.7320
7.0	0.7458
10.0	0.7597

It will be convenient to express the Compton electron average forward range R for a gamma energy E_γ as

$$\overline{R} = \zeta(E_\gamma)\ R_{ex}(\overline{E})\ \overline{\cos\phi} \ .$$

where the extrapolated range R_{ex} is determined from the average Compton electron energy E, the Compton electron average forward direction cosine $\overline{\cos\phi}$ is determined from the gamma energy, and the factor ζ is determined from the gamma energy. Once $\overline{R}$, $\overline{E}$, and $\overline{\cos\phi}$ are known, ζ is readily found.

3. RESULTS OF CALCULATION

The integrals for σ_e, $\overline{E}$, $\overline{\cos\phi}$, and $\overline{R}$ were integrated numerically for a range of gamma ray energies from 0.01 to 10.0 MeV. This was done both for the extrapolated range R_{ex} and the esti-

[1] *John S. Malik, The Compton Current, Los Alamos Scientific Laboratory, Defense Atomic Support Agency, 1882- (5 November 1965).*

mated extrapolated range $0.8R_o$, since expressions for R_{ex} and $0.8\,R_o$ yield somewhat different values. Results are shown in table 2 for R_{ex} and in table 3 for $0.8\,R_o$. In addition to $\overline{E}$, $\overline{\cos\phi}$, and $\overline{R}$, the results include the factor ζ, and also the value for $\overline{R}$ that is obtained if an energy-independent ratio $\hat{R}/R_{ex} = 2/3$ is used.

Comparison of $\overline{R}$ with $\overline{R}\,(\hat{R}/R_{ex} = 2/3)$ shows the effect of neglecting the energy dependence of the transmission factor. The difference is negligible for a gamma energy of 1.5 MeV, and increases the more the energy level differs from 1.5 MeV. For example, the difference is 7 percent for gamma energies of 0.3 MeV, 5 percent for 0.7 MeV, 5 percent for 3.5 MeV, and 10 percent for 7 MeV. The value for $\overline{R}\,(\hat{R}/R_{ex} = 2/3)$ is too low at higher gamma energies and at very low gamma energies. This is understandable since (1) at high gamma energies most recoil electrons are scattered nearly forward with energies so high that $\hat{R}/R_{ex} = 2/3$ is an underestimate, and (2) at very low gamma energies for which Compton recoil energies approach 0.02 MeV, the Ebert formula for the transmission factor begins to fail (predicting an increase in $\hat{R}/R_{ex}$ to a value of 0.749 at E = 0.03 MeV, for example). The failure in the Ebert formula is due to the quantity 1/B approaching and exceeding unity. For this reason, the computation cannot reasonably be applied to gamma energies less than about 0.3 MeV.

TABLE 2. COMPUTED RESULTS USING ELECTRON EXTRAPOLATED RANGE[a]

E_γ (MeV)	ζ_{ex}	$\overline{E}$ (MeV)	ρR_{ex} (g/cm²)	$\overline{\cos\phi}$	$\rho\overline{R}$ (g/cm²)	$\rho\overline{R}$ for $\hat{R}/R_{ex} = 2/3$ (g/cm²)
0.01	2.181	0.188(−3)	0.666(−7)	0.656	0.953(−7)	0.635(−7)
0.1	1.461	0.0138	0.516(−3)	0.654	0.492(−3)	0.383(−3)
0.15	1.137	0.0272	0.171(−2)	0.658	0.128(−2)	0.122(−2)
0.2	1.025	0.0433	0.374(−2)	0.663	0.255(−2)	0.261(−2)
0.3	0.937	0.0809	0.0103	0.677	0.655(−2)	0.699(−2)
0.4	0.897	0.124	0.0200	0.692	0.0124	0.0133
0.5	0.873	0.171	0.0325	0.707	0.0200	0.0214
0.6	0.857	0.221	0.0473	0.721	0.0292	0.0309
0.7	0.844	0.273	0.0643	0.733	0.0398	0.0418
0.8	0.834	0.327	0.0831	0.745	0.0516	0.0539
1.0	0.820	0.440	0.125	0.766	0.0787	0.0811
1.5	0.799	0.742	0.251	0.807	0.162	0.162
2.0	0.787	1.062	0.397	0.835	0.261	0.257
2.5	0.781	1.393	0.555	0.856	0.371	0.360
3.0	0.777	1.732	0.721	0.872	0.489	0.468
3.5	0.775	2.077	0.893	0.885	0.612	0.580
5.0	0.771	3.140	1.431	0.911	1.005	0.931
7.0	0.771	4.597	2.167	0.931	1.556	1.412
10.0	0.773	6.836	3.273	0.948	2.399	2.133

[a] *Symbols are defined as follows.*

E_γ = *gamma energy*
ζ_{ex} = *correction factor obtained for* $\rho\overline{R} = \zeta_{ex}\rho R_{ex}(\overline{E})\,\overline{\cos\phi}$
$\overline{E}$ = *average recoil electron energy*
ρR_{ex} = *extrapolated range for electron energy* E, *air density* ρ
$\overline{\cos\phi}$ = *Compton electron forward direction cosine*
$\rho\overline{R}$ = *Compton electron average forward range for transmission factor* T(E), *air density* ρ

It is emphasized that these results for the average forward range of Compton electrons are valid only for incident collimated monochromatic gamma rays undergoing a first scatter. Subsequent scatters would occur at lower gamma energies and in different directions than for the first scatter. However, accurate Compton electron current scores could be obtained from multiple-scatter gamma transport calculations if the Compton electron average forward range presented here were used to score each Compton scatter.

The expression

$$\bar{R} = \zeta(E_\gamma)R_{ex}(\bar{E})\overline{\cos\phi}$$

uses the fit to the extrapolated range $R_{ex}(E)$ in air for the average Compton recoil energy $\bar{E}$; in this expression, the factor $\zeta(E_\gamma)$, a function of the incident gamma energy E_γ (in MeV), is approximated to within ±0.003 on the interval $0.3\ \text{MeV} \leq E_\gamma \leq 10\ \text{MeV}$ by

$$\zeta_{ex} \simeq 1.22/(1+1.2065x-0.626x^2) \quad .$$

where

$$x = E_\gamma/(E_\gamma+0.7) \ .$$

When the extrapolated range is estimated as $0.8R_o(E_\gamma)$ where R_o is Longmire's fit to the CSDA range, the factor ζ is approximated to within ±0.003 on the same interval by

TABLE 3. COMPUTED RESULTS USING ELECTRON CSDA RANGE[a]

E_γ (MeV)	ζ_o	$\bar{E}$ (MeV)	$0.8\rho R_o$ (g/cm²)	$\overline{\cos\phi}$	$\rho\bar{R}$ (g/cm²)	$\rho\bar{R}$ for $R/R_{ex} = 2/3$ (g/cm²)
0.01	1.877	0.188(−3)	0.660(−7)	0.656	0.813(−7)	0.542(−7)
0.1	1.569	0.0138	0.339(−3)	0.654	0.348(−3)	0.272(−3)
0.15	1.234	0.0272	0.126(−2)	0.658	0.102(−2)	0.984(−3)
0.2	1.112	0.0433	0.301(−2)	0.663	0.222(−2)	0.229(−2)
0.3	1.000	0.0809	0.937(−2)	0.677	0.635(−2)	0.678(−2)
0.4	0.940	0.124	0.0195	0.692	0.0127	0.0136
0.5	0.900	0.171	0.330	0.707	0.0210	0.0224
0.6	0.872	0.221	0.494	0.721	0.0310	0.0328
0.7	0.851	0.273	0.0681	0.733	0.0425	0.0447
0.8	0.835	0.327	0.0889	0.745	0.0553	0.0577
1.0	0.813	0.440	0.135	0.766	0.0841	0.0866
1.5	0.786	0.742	0.268	0.807	0.170	0.171
2.0	0.775	1.062	0.416	0.835	0.269	0.265
2.5	0.770	1.393	0.573	0.856	0.378	0.366
3.0	0.768	1.732	0.735	0.872	0.492	0.471
3.5	0.767	2.077	0.901	0.885	0.612	0.580
5.0	0.769	3.140	1.415	0.911	0.991	0.918
7.0	0.773	4.597	2.123	0.931	1.528	1.387
10.0	0.779	6.836	3.214	0.948	2.375	2.111

[a] *Symbols are defined as follows.*

E_γ = *gamma energy*
ζ_o = *correction factor obtained for* $0.8\rho\bar{R} = \zeta_o 0.8\rho R_o(\bar{E})\ \overline{\cos\phi}$
$\bar{E}$ = *average recoil electron energy*
$0.8\rho R_o$ = *estimated extrapolated range from CSDA range* R_o *for electron energy* $\bar{E}$, *air density* ρ
$\overline{\cos\phi}$ = *Compton electron average forward direction cosine*
$\rho\bar{R}$ = *Compton electron average forward range for transmission factor* $T(E)$, *air density* ρ

$$\zeta_o \approx 1.7664/(1+3.0899x-1.8462x^2) ,$$

where x is defined as before.

The average forward direction cosine $\overline{\cos\phi}$ is approximated to four significant figures on the interval $0.1 \text{ MeV} < E_\gamma \leq 10 \text{ MeV}$ by

$$\overline{\cos\phi} \simeq \frac{0.660362-0.089254\mu+0.098517\mu^2}{1.0 - 0.183651\mu + 0.105445\mu^2} ,$$

where

$$\mu = \ln[0.5+3.7\ E_\gamma^2/(E_\gamma+0.05)] .$$

The average recoil energy $\bar{E}$ is exactly calculable as

$$\bar{E} = E_\gamma \sigma_e^{(a)}/\sigma_e ,$$

where $\sigma_e^{(a)}$ is the Klein-Nishina Compton absorption cross section.

4. CONCLUSIONS

In this investigation, an energy-dependent electron transmission factor has been used to evaluate more accurately the Compton electron average forward range, for incident gamma energies from 0.3 to 10.0 MeV. The results were compared with a popular previous approximation using an energy-independent electron transmission factor. The previous approximation shows in comparison essentially no error for a gamma energy of 1.5 MeV, 7 percent error for 0.3 MeV, and 10 percent error for 10.0 MeV.

For a typical gamma spectrum hardened to an average energy of about 3.5 MeV by atmospheric attenuation of lower energies, the previous approximation would give Compton currents 5 percent smaller and electric fields perhaps 10 percent smaller than for the more accurate treatment presented here. Although the differences are small, the more accurate estimate of average forward range presented here could be incorporated into EMP environment prediction codes at virtually no cost. Simple numerical fits to relevant parameters are given.

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